BOTTOMS OR TOPS? –OPTIMISING LOCATION OF WETLANDS IN CATCHMENTS TO MAXIMISE EFFICIENCY

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Abstract
One of the key ecosystem services wetlands can provide in agricultural landscapes is attenuation of flows and diffuse pollutant loads. The answer as to where in agricultural catchments wetlands should optimally be located for water quality enhancement varies depending on the landscape of interest, the flow regime, and the particular contaminants being targeted. Recognising that hydrology is the most fundamental factor influencing pollutant removal performance, a simple dynamic model for wetland pollutant removal was used to explore potential wetland nitrate removal performance from surface waters at various locations within an agricultural catchment. Annual nitrate removal performance over two annual periods were compared at up- and down-stream locations within two Waikato catchments with contrasting flow regimes where contemporaneous hourly flow records were available. Overall performance is shown to be substantially better when flows are steady or show low variability. This suggests that wetland performance for nitrate-N will tend to be better near the bottom of catchments where flow regimes tend to be more buffered than they are at the top of catchments. A range of other considerations will also influence the costs and benefits of top and bottom-of-catchment wetlands including: targeting of critical source areas, equitable spread of costs across landowners and biodiversity benefits.

Introduction
Surface-flow wetlands have been shown in numerous studies to be effective at removing nutrients (Mitsch et al. 2005, O'Geen et al. 2010, Jordan et al. 2011, Kadlec 2012).The question of where wetlands should optimally be located in agricultural catchments to intercept and attenuate diffuse nutrient losses (see Figure 1) was posed more than 20 years ago by Mitsch (1992) and van der Valk and Jolly (1992), but has never been clearly resolved. This is likely because the answer changes depending on the landscape of interest, the particular contaminants being targeted, the range of associated ecosystem services sought (e.g. biodiversity, flood control), and the policy environment in which it is being considered (Mitsch and Gosselink 2000, Crumpton 2001, Blackwell and Maltby 2003, Zedler 2003, Hansson et al. 2005, Moreno-Mateos and Comin 2010, O'Geen et al. 2010).

The relative area of wetlands required to effectively remove excess nutrients is commonly proposed to be in the range of 0.1-5% of the contributing catchment (Kadlec and Wallace 2009). Removal of sediment-associated contaminants, such as phosphorus and faecal microbes, occurs primarily by physical settling and can often be achieved in relatively small wetlands (Braskerud 2001, 2002). In contrast, removal of dissolved contaminants such as nitrate depends on biogeochemical processes, generally requiring longer residence times and so larger wetland areas (Kadlec 2012).

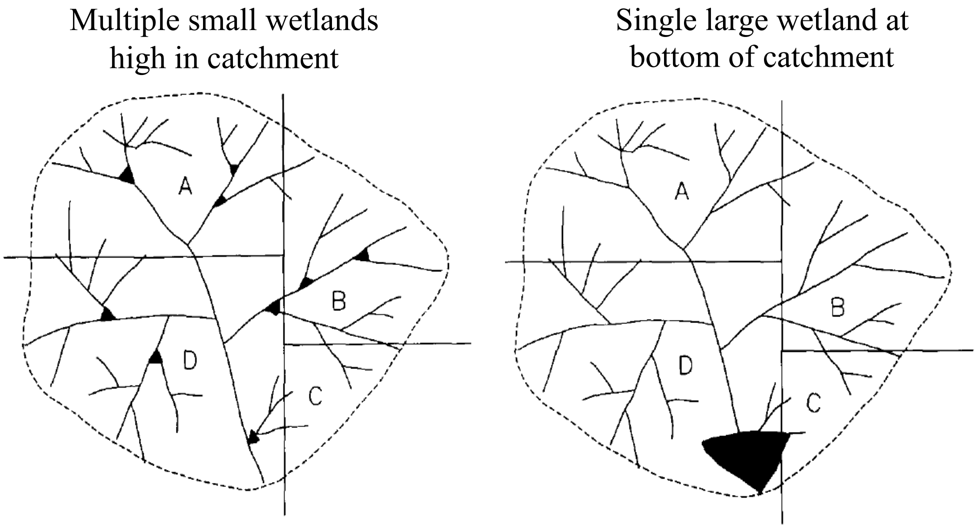

Figure 1: Which location will provide the best treatment outcomes: multiple small distributed top-of-catchment wetlands or single large downstream wetlands? Diagram from van der Valk and Jolly (1992)

Wetlands have been identified as useful tools to intercept and attenuate nitrate-rich agricultural runoff. Anoxic conditions created in organic-rich sediments and litter create ideal conditions for microbial nitrification, thereby providing a sustainable means of returning excess nitrogen back to the atmosphere. Wetland nitrate removal performance, modulated by water temperature, is known to be significantly affected by the residence time of through-flowing waters and generally increases with wetland size (Kadlec 2012).

Knowing that flows tend to become attenuated as they move from upstream to downstream locations (Figure 2), we investigated whether these differences would affect wetland nitrate removal at upstream and downstream locations within two agricultural catchments.

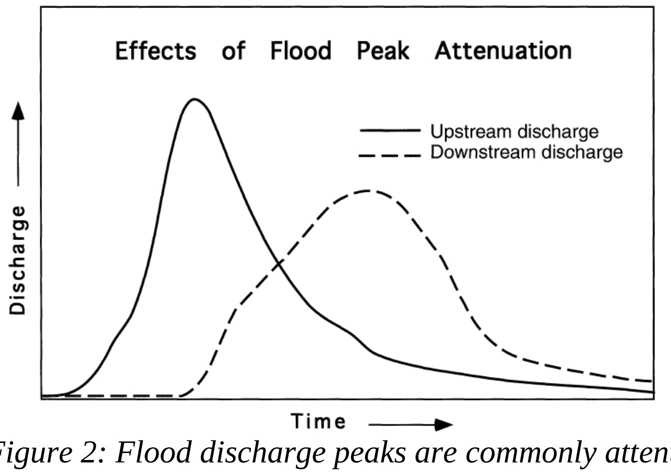

Figure 2: Flood discharge peaks are commonly attenuated as they move through catchments. Will this influence wetland treatment performance at upstream and downstream locations in a catchment? Diagram from Woltemade (1994).

Methods

A simple dynamic model for wetland pollutant removal operating on a hourly time step, as described in Tanner and Kadlec (2013), was used to explore potential wetland nitrate removal performance at various locations within an agricultural catchment focussing on the response to differing hydrological regimes. The model had been tested and calibrated using data from New Zealand wetlands treating subsurface drainage from dairy farms (Tanner et al. 2005, Tanner and Sukias 2011). Annual nitrate removal performance over two annual periods were compared at up- and down-stream locations within two Waikato catchments with contrasting flow regimes where contemporaneous hourly flow records were available (Figure 3). To enable direct comparison, flows were standardised so they represented the same total yield per ha and same nitrate load, but different flow variability.

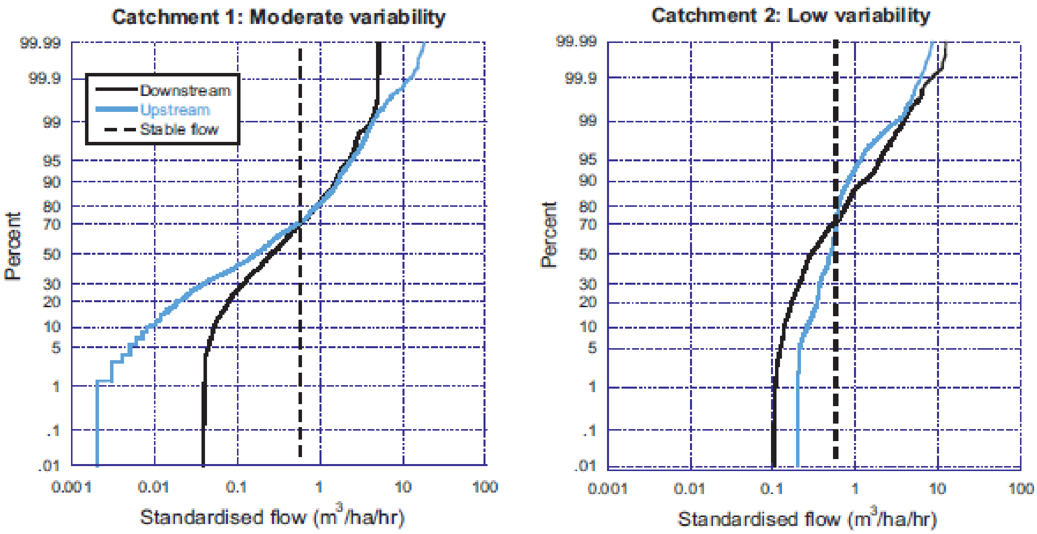

Figure 3: Percentile plots of flow variability for two Waikato catchments (C1 & C2) from Tanner and Kadlec (2013).

Results and Discussion

The characteristic pattern of increasing flow buffering as you move down a catchment is evident for our test Catchment 1 (C1; Figure 3Figure 3: Percentile plots of flow variability for two Waikato catchments (C1 & C2) from Tanner and Kadlec (2013). with normalised upstream flows (m^2 ha^{-1}yr^{-1}) showing a greater proportion of low and high flow extremes than downstream flows. In contrast, test Catchment 2 (C2; Fig 8b) shows considerably reduced flow variability for the upstream sub-catchment, in particular less extreme low-flows. Both the C1 and C2 downstream sites show similar overall coefficients of variation and baseflow indexes, but catchment C2 shows considerably more stable baseflow (see Tanner and Kadlec 2013 for comparative statistics)

The modelled wetlands showed best overall performance when flows were steady or exhibited very low variability (e.g. C2 upstream; Figure 4). The wetlands receiving the moderate variability C1 flow regimes showed substantially poorer percentage and mass load reductions, and higher outlet nitrate-N concentrations than those receiving the low variability C2 flow regimes. Under the most variable C1 upstream flow regime nitrate-N removal efficiency for wetlands occupying 1–4% of catchment area was reduced by 14–21 percentage points, respectively, compared to those predicted under steady flow. The significance of this is most obvious when you consider that the maximum annual mass removal for a wetland occupying 5% of catchment area under the most variable flow regime (~22.5 kg ha^{-1} of catchment for C1 upstream @ 50 kg ha^{-1} catchment loading) could theoretically have been achieved under the least variable flow regime (C2 upstream; but same total flow and mass load) with a wetland occupying only about 1.7% of the catchment (Fig. 11). In this particular case, the areal mass removal achieved by the 1.7% wetland with the least variable flow would be 140 g nitrate-N m^{-2} yr^{-1}, while the 5% wetland receiving the most variable flow was operating at less than 50 g nitrate-N m^{-2} yr^{-1} (Figure 5).

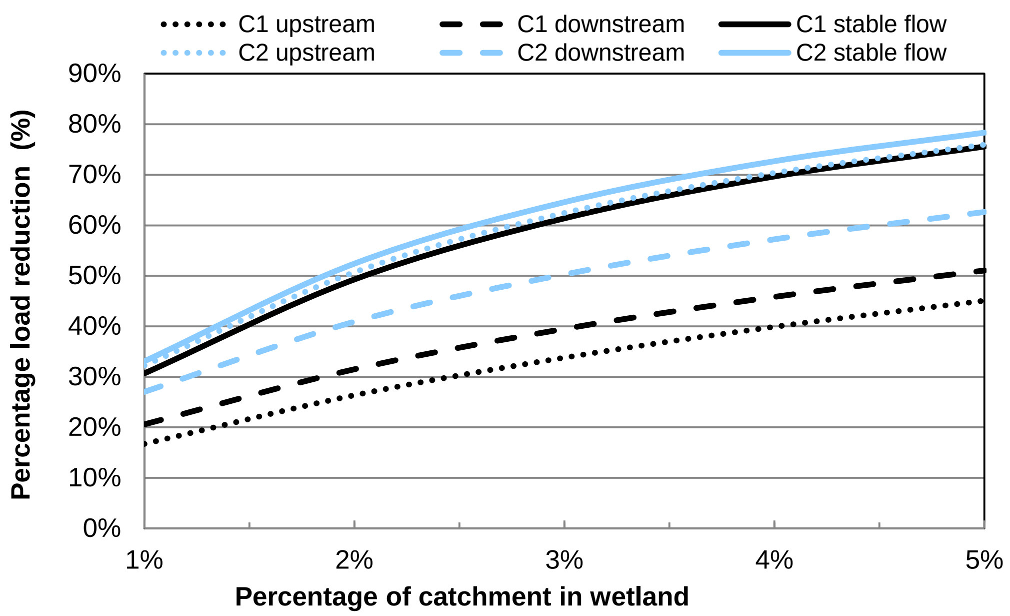

Figure 4: Comparison of predicted wetland load reduction performance for different relative wetland size, flow regime (C1 moderate variability; C2 low variability) and catchment location (upstream and downstream)

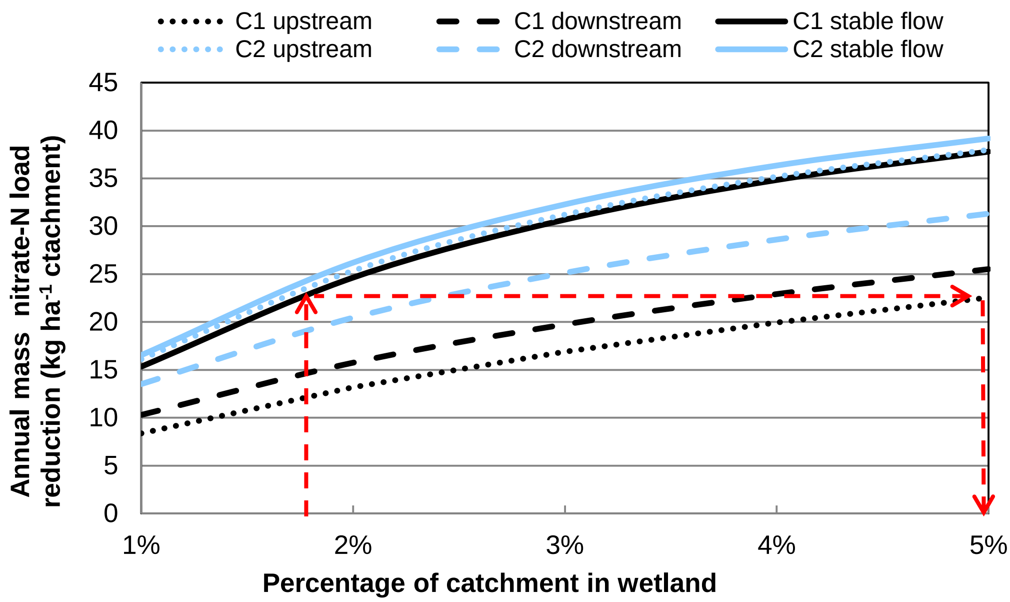

Figure 5: Comparison of predicted wetland nitrate-N mass load reduction for different relative wetland size, flow regime (C1 moderate variability; C2 low variability) and catchment location. Based on annual catchment water yield of 500 mm and annual catchment nitrate-N yield of 50 kg/ha. The red dashed lines show the increase in relative wetland size required under high variability flow (C1 upstream) to achieve the same load reduction predicted for the wetland receiving the least variable flow regime (C2 upstream)

Table 1: Summary of advantages and disadvantages of different wetland locations

Multiple top of catchment wetlands

- Target source areas
  - SS, PP hotspots
  - Protects whole downstream channel
  - Moderate downstream flows
- Equitable spread across landowners
  - All contribute land and cover own costs
- Smaller-scale wetlands able to be built simply using practical know-how and resources of farmers and agricultural contractors
  - Able to be phased in across a farm
  - Low risk
- Increase biodiversity across whole farm landscape
  - Connectivity through & between catchments

Large bottom of catchment wetland

- Directly target high value water resources –e.g. lakes, estuaries
  - Greater chance for community engagement
- Intercepts majority of diffuse load
- Flow less variable
  - Improved treatment efficiency
- Fewer land-owners directly impacted
  - One farm targeted
  - Potential to use lowest value land
- Economy of scale: construction of large wetlands cheaper per ha & kg N removed
  - Design and construction likely to be more complex
- Biodiversity more localised

The model simulations presented illustrate how flow regimes in catchments with different climate and hydrogeology, and at different locations within catchments can significantly influence the treatment efficacy of wetlands, and the relationship between wetland size and removal performance. This will affect both the level of treatment practically achievable by wetlands, and the consequent cost:benefit ratio of wetland construction and rehabilitation.

The results from this modelling study predict that wetlands receiving steady flows of diffuse nitrate-rich run-off (e.g. high proportion of consistent base-flow) will show the best nitrate-N removal performance. Those receiving very “flashy” and inconsistent flows will show reduced performance. This suggests that wetland performance for nitrate-N will generally be better near the bottom of catchments where flow regimes tend to be more buffered than they are at the top of catchments. As outlined in Table 1, a wide range of other considerations will also influence the costs and benefits of top and bottom-of-catchment wetlands, including: targeting of critical source areas, equitable spread of costs across landowners and biodiversity benefits. Broader discussion on the potential role of wetlands in agricultural landscapes can be found in the recent Special Issue of *Ecological Engineering*, “Bringing Together Science and Policy to Protect and Enhance Wetland Ecosystem Services in Agricultural Landscapes” (Tanner et al. 2013).

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